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Lutetian Limestones in the Paris Region: Petrographic and Compositional Examination

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Stone for building and decorating monuments in the Paris Basin from antiquity to the present came from numerous quarries in the Lutetian limestone formations of the region. To identify specific stone sources used for masonry and sculptures in these monuments, a team of geologists and archaeologists has investigated 300 quarries and collected 2300 limestone samples for study in a collaborative effort by geologists and chemists.

Petrographic and paleontologic examinations of thin sections enable geologists to distinguish the Tertiary Lutetian limestones from similar stone in Jurassic and Cretaceous strata. The methods of the geologist have been supplemented by those of the chemist whose compositional studies by neutron activation analysis can differentiate among the fine-grained upper Lutetian limestones extracted from specific ancient quarries.

GEOLOGY OF LUTETIAN LIMESTONES

Lutetian limestones were deposited in the warm sea that covered the Paris region approximately 45 million years ago. The term 'Lutetian', assigned to this formation by nineteenth-century geologists, comes from the Roman name for Paris: Lutetia. The Lutetian stratum is divided into several substrata. In Paris the limestones of the Upper Lutetian layer, characterized by *Miliolidae* (a suborder of foraminifera) furnished much of the stone for construction and statuary.

Parisian limestone sources were exploited as open quarries along the banks of the rivers that flowed through Paris, the Seine and the Bièvre, from antiquity to the beginning of the Middle Ages (Fig. 1). Gradually the quarries were extended to subterranean galleries cut beneath the fields beyond the city walls. These galleries still exist below the modern city (Blanc and Lorenz 1988, 1990), allowing us to examine the ancient quarry faces.

Because the galleries are still accessible, our team of geologists and quarry historians has been able to investigate the quarries in Paris and the surrounding region, and collect samples for study in the laboratory (Blanc and Gely 1997). These studies of the terrain have allowed us to identify the layers producing stone suitable for construction:

bancs francs, banc de roche, and lamboursdes; and those layers of fine-grained stone used for sculpture: liais and banc royal (Fig. 2).

PETROGRAPHIC STUDY OF LUTETIAN LIMESTONES

Microscopic examination of thin sections shows that all Lutetian layers consist of pellet-formaniferal limestones while substrata exhibit recognizable lithologic differences. This holds true for the quarries of Paris as well as those in the city's immediate environs such as those at Montrouge, Arcueil, Charenton, and Saint-Maurice.

Substrata in Parisian quarries

Lambourdes is soft chalky limestone (Fig. 3c). Certain layers are rich in *Miliolidae* and also incorporate another large foraminifer: *Orbitolites complanatus* (Fig. 4c). Other layers consist solely of fine bioclasts in a porous micritic matrix.

Liais is a stone known for its hardness. In thin section its bioclasts and *Miliolidae* are small (approximately 0.1mm) and surrounded by a non-porous microsparitic matrix (Fig. 3b).

Bancs francs stone is rich in foraminiferans, such as *Miliolidae* and *Textularidae*, but contains no *Orbitolites*. A typical banc franc layer approximately forty to forty-five centimeters thick, may contain one or two substrata, each two to three centimeters thick and rich in fossil impressions of gastropods (Fig. 3a).

Banc de roche stone is hard and very rich in gastropod shells uniformly distributed throughout. It also includes remnants of the stems of *Characea* (aquatic plants).

Substrata in other Lutetian limestone sources

The artisans who built monuments in the Ile-de-France took stone not only from Parisian quarries, but also from the Lutetian layers to the north and east of the city (Fig. 5).

In the valley of the Oise River approximately 50 kilometers north of Paris, quarries in the Middle Lutetian layers produced stone for Parisian monuments beginning in the fourteenth century. This stone incorporates a trace fossil *Ditrupa strangulata* (Figs. 4a, 4b), which distinguishes it from the Upper Lutetian layers identified by *Miliolidae*.

Limestone deposits near Noyon are distinguished by higher concentrations of small quartz crystals than found in other quarries in the Paris region.

At Laon and in the ancient quarries south of that city, the Lutetian limestone contains foraminiferans (*Nummulites* and *Orbitolites complanatus*), tubes of *Ditrupa,* and shells of bivalve mollusks.

The ancient quarries near Reims are located approximately 15 kilometers northwest of the city. Their stone is slightly more yellow than Parisian stone, and in addition to *Miliolidae* incorporates large concentrations of the remains of white bivalve mollusks.

COMPOSITIONAL ANALYSIS

In the search for sources of stone for building and sculpture, the analytic methods of geologists and petrographers are limited because they do not adequately distinguish among the fine-grained Upper Lutetian limestones. In thin section lithofacies from quarries of lambourdes stone at or near Carrières-sur-Seine, Conflans-Sainte-Honorine, Courville and Senlis appear as similar pellet-foraminiferal limestones. Distinction among such similar limestones from geographically separate sources is possible by compositional analysis, however. Geologists and chemists are therefore collaborating to answer the questions of art historians and museum curators about the origin of sculpture carved in stone from the Paris region.

Neutron-activation analysis of limestone

Limestones from different sources have distinctive patterns of trace-element concentrations. Thus, compositional analysis by neutron activation allows us to compare building or sculptural stone from one monument with stone from quarries or other monuments.

In this process neutrons bombard encapsulated samples of limestone powder. The neutrons are captured by the nuclei of atoms present in the stone, producing radioactive isotopes which emit characteristic gamma rays in the course of achieving stability. From the resulting gamma spectrum we can calculate a compositional profile characteristic of that stone. (The process is described in detail in Holmes *et al.* 1986.)

The method has the advantages that:

- it requires only a one-gram sample of powdered stone;
- it determines approximately 20 elemental concentrations useful for multivariate statistical analysis;
- its sensitivity allows us to quantify constituents present in micrograms/gram sample or even smaller concentrations.

Multivariate statistical analysis of data

To infer the geographic origin of a sculpture based on the composition of its stone one must define discrete compositional groups to which a sample of unknown provenance may be compared. If these groups vary widely in the concentrations of several elements, they may readily be distinguished by plotting pairs of elemental concentrations for each sample in the group.

Differentiation among stone sources within a relatively uniform geological formation such as the Paris Basin, however, requires more sophisticated mathematical approaches. One such approach involves the linear combination of the concentrations of many elements to calculate a set of 'principal components' in multidimensional Mahalanobis space. For these calculations, each analyzed sample is designated as one point in multidimensional compositional space. This space is defined by the concentrations of those elements for which limestone exhibits significant and reproducible differences. In such a space, samples with similar compositions lie close together while samples with dissimilar compositions lie further apart. This procedure has several additional advantages (Fig. 6):

- **it incorporates all the useful concentration information available for each sample;**
- **fewer combinations need to be plotted than are required by a purely two-dimensional approach;**
- **clearer distinctions among groups result.**

A third alternative is the combination of the concentrations of many elements according to a different set of mathematical relationships to calculate 'canonical functions' in multivariate Discriminant space (Fig. 7). This method

- **maximizes differences among most groups;**
- **permits statistical analysis with fewer samples per group.**

It should be emphasized that all multivariate statistical procedures require

- **many elements (ten to fifteen elements seem to characterize limestone best);**
- **many samples for each compositional group (Sneath & Sokal 1971).**

Examples of provenance determination by trace-element analysis

Neutron activation analysis allows us to distinguish among limestones that are petrographically identical, such as those found in the quarries of Paris and its environs (Fig. 5):

- **in the Val-de-Grâce section of Paris**
- **at Charenton**
- **at Arcueil**
- **at Carrières-sur-Seine**
- **at Conflans-Sainte-Honorine**
- **at Saint-Ouen-l'Aumône.**

We have used Discriminant analysis to differentiate among groups of samples from these locations. For instance, a plot of concentration data in Discriminant space (Fig. 8) illustrates that stone from the quarries at Charenton, Carrières-sur-Seine, and Conflans-Sainte-Honorine can be distinguished, and that samples from sculptures on the west-facade portals of Notre-Dame, Paris, may have come from the ancient quarries at Charenton.

Museum collections include many sculptures whose origins are shrouded in mystery. Because samples of stone are available for comparison, it is often possible to identify the French monuments which such sculptures originally embellished. A Mahalanobis search of the Brookhaven Limestone Database allowed us to assign a Notre-Dame origin to the head of an Angel in the collections of The Metropolitan Museum of Art (Fig. 9), a choir screen now in the Musée du Louvre, and the head of a Virtue in the Duke University Museum of Art (Little 1994). The results of that search are summarized in Figure 10).

Groups of samples from quarries near Senlis, near Noyon, and in the Oise River valley also differ in composition. These differences allowed us to localize four statues in American museums. Stone from the Moses figure at The Cloisters Museum in New

York resembles limestone from Noyon, as does the statue of the Virgin still at the Cathedral of Noyon. The statue of Aaron at The Metropolitan Museum of Art more closely resembles stone from Senlis, while the figure of a prophet at the Duke University Museum of Art may have been carved in stone from quarries in the Oise River valley (Little 1994).

While the west facade of the Cathedral of Notre-Dame at Reims was undergoing restoration, samples were collected from the archivolts of the central portal. Trace-element analysis shows a difference in composition between the limestones used for the statues at the base of the archivolts and those in the upper levels. This difference was apparent to the restorers while they worked, but it was very subjective, difficult to describe, and certainly not quantifiable. The difference in composition probably corresponds to a change in quarries and perhaps also to an interruption of several years in construction.

Stone has been analyzed from monuments in other regions in France: quarries and monuments in the vicinity of Caen, of areas of Burgundy, and of regions in southwestern France. Clearly, the work to date demonstrates that collaboration between geologists and chemists, using a combination of petrographic and

compositional analysis, opens new paths for art historical research. We hope to continue similar collaborative work to advance the art historian's knowledge of the geologic origins and source locations of medieval architectural and decorative stone.

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FIGURE CAPTIONS

Figure 1.

Map of old Parisian quarries near the rivers that flowed through the city, the Seine and the Bièvre.

Figure 2.

Limestone strata in an old quarry in the south of Paris, beneath the rue de la Santé. The 'lambourdes' were extracted from the lower gallery; 'liais' and 'bancs francs' stone came from the upper gallery. The 'banc de roche' stone constituted the roof of the upper gallery.

Figure 3.

Photomicrographs of Lutetian limestone from old quarries in southern Paris:

a. 'Bancs francs': *Miliolidae* and other foraminiferans.

b. 'Liais': fine-grained limestone with small *Miliolidae.*

c. 'Lambourdes': micritic limestone with debris of *Miliolidae.*

Figure 4.

Photomicrographs of 'Banc de Saint-Leu' Lutetian limestone from Oise River valley, used in the Hôtel des Invalides in the eighteenth century:

a, b. Biomicritic limestone with worm tube (*Ditrupa*) and *Miliolidae.*

c. *Orbitolites complanatus*.

Figure 5.

Quarry locations in the Lutetian limestone formation of the Paris Basin.

Figure 6.

Plot of concentration data in Mahalanobis space, showing the two 'principal components' that best distinguish groups of samples from four quarries near Paris.

Figure 7.

Plot of concentration data in Discriminant space, showing that two 'canonical Discriminant functions' are effective in distinguishing groups of samples from four quarries near Paris.

Figure 8.

Plot of data in Discriminant space, showing that the composition of stone from medieval sculpture at Notre-Dame's west facade is consistent with an origin in the quarries at Charenton.

Figure 9.

Head of an Angel (The Metropolitan Museum of Art acc. no. 1990.132)

Figure 10.

Compositional profile of the Notre-Dame reference group compared with the profiles of three sculptures now in museum collections.

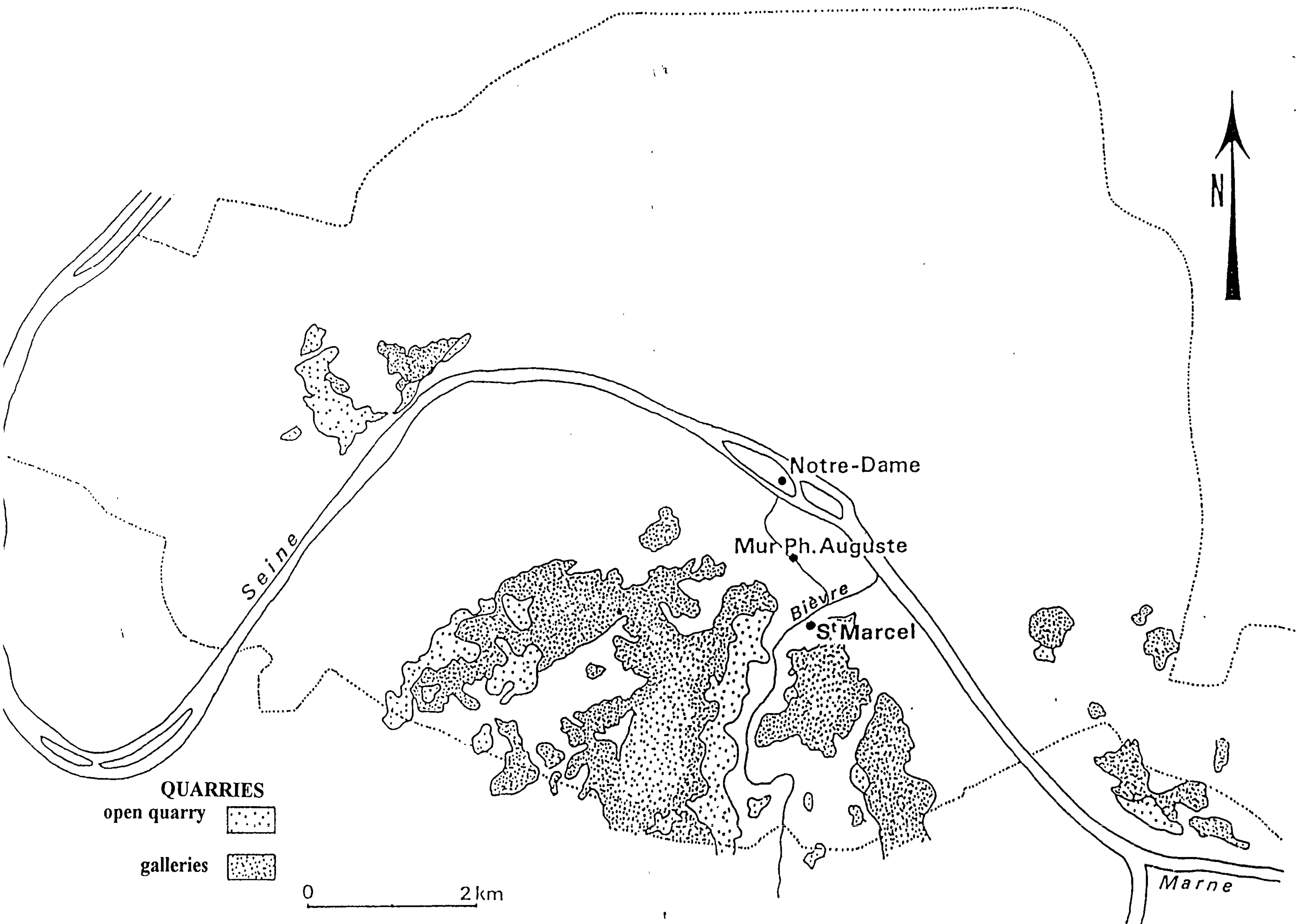
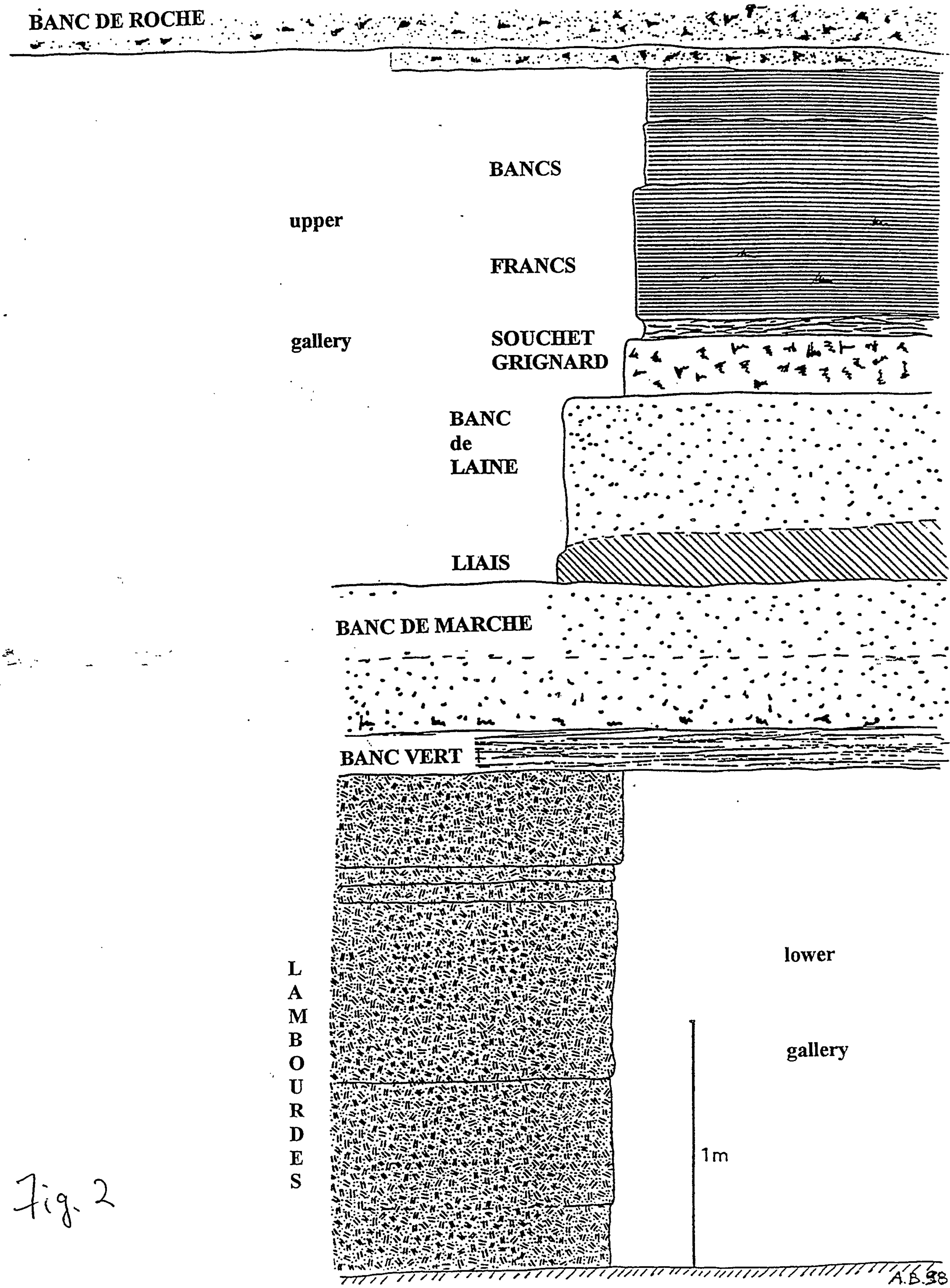

N
Notre-Dame
Mur Ph. Auguste
Bièvre
St Marcel
Seine
Marne
QUARRIES
open quarry
galleries
0
2 km

Fig. 1



BANC DE ROCHE
BANCS
upper
FRANCS
gallery
SOUCHET
GRIGNARD
BANC
de
LAINE
LIAIS
BANC DE MARCHE
BANC VERT
L
A
M
B
O
U
R
D
E
S
lower
gallery
1m
A.B.98

Fig. 2

LUTETIAN LIMESTONES

OLD QUARRIES IN THE SOUTHERN PART OF PARIS

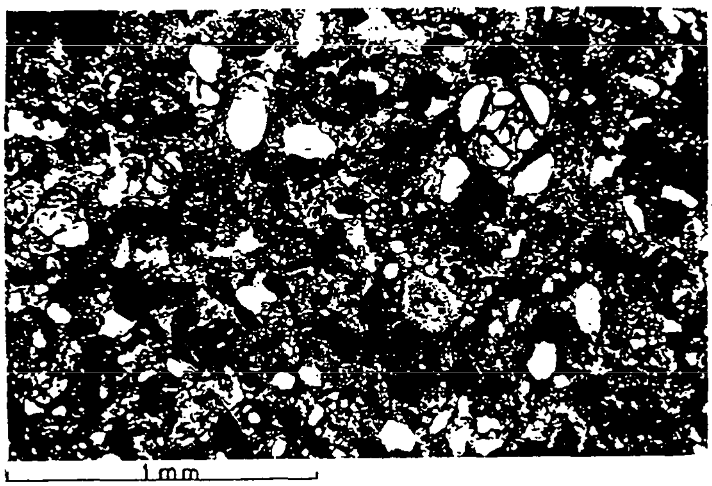
3a.

« BANC FRANC »

Miliolids

Foraminifers

3b.

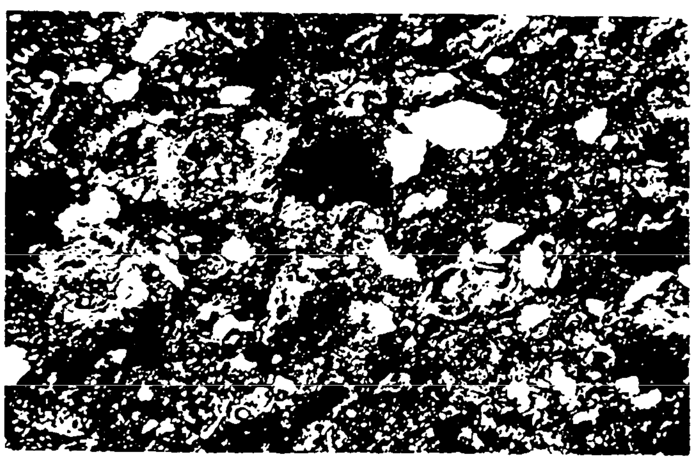


« LIAIS »

fine limestone

with small Miliolids

3c



« LAMBOURDES »

micritic limestone

debris of miliolids

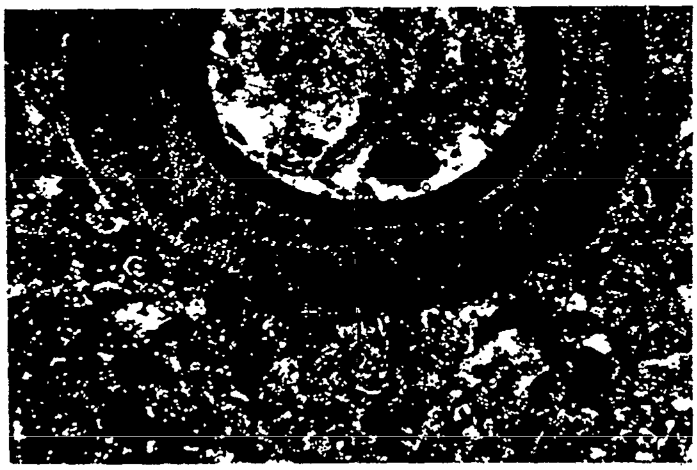
Fig. 3

LUTETIAN LIMESTONES

BANC DE SAINT-LEU

used in Paris for the Hôtel des Invalides, XVIIth c.

4a.

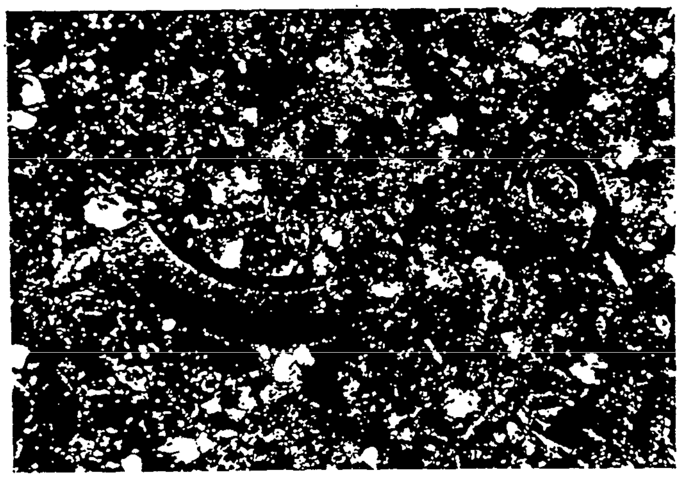


Worm tube :

Ditrupa

Miliolids

4b.

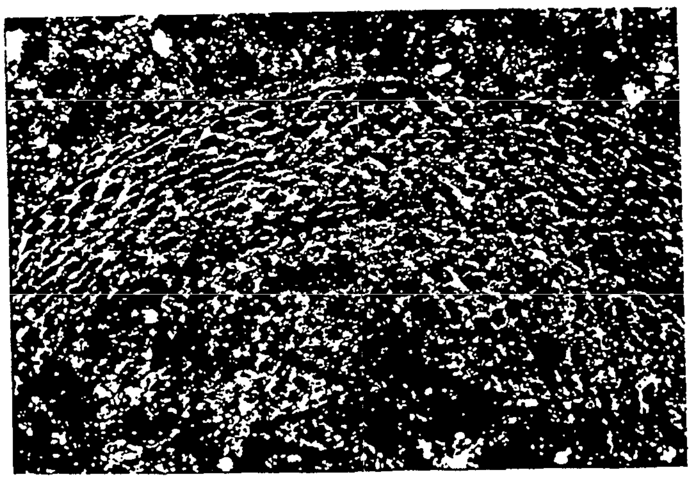


Biomicritic limestone

Miliolids

Ditrupa

4c.



Orbitolites complanatus

Fig.4

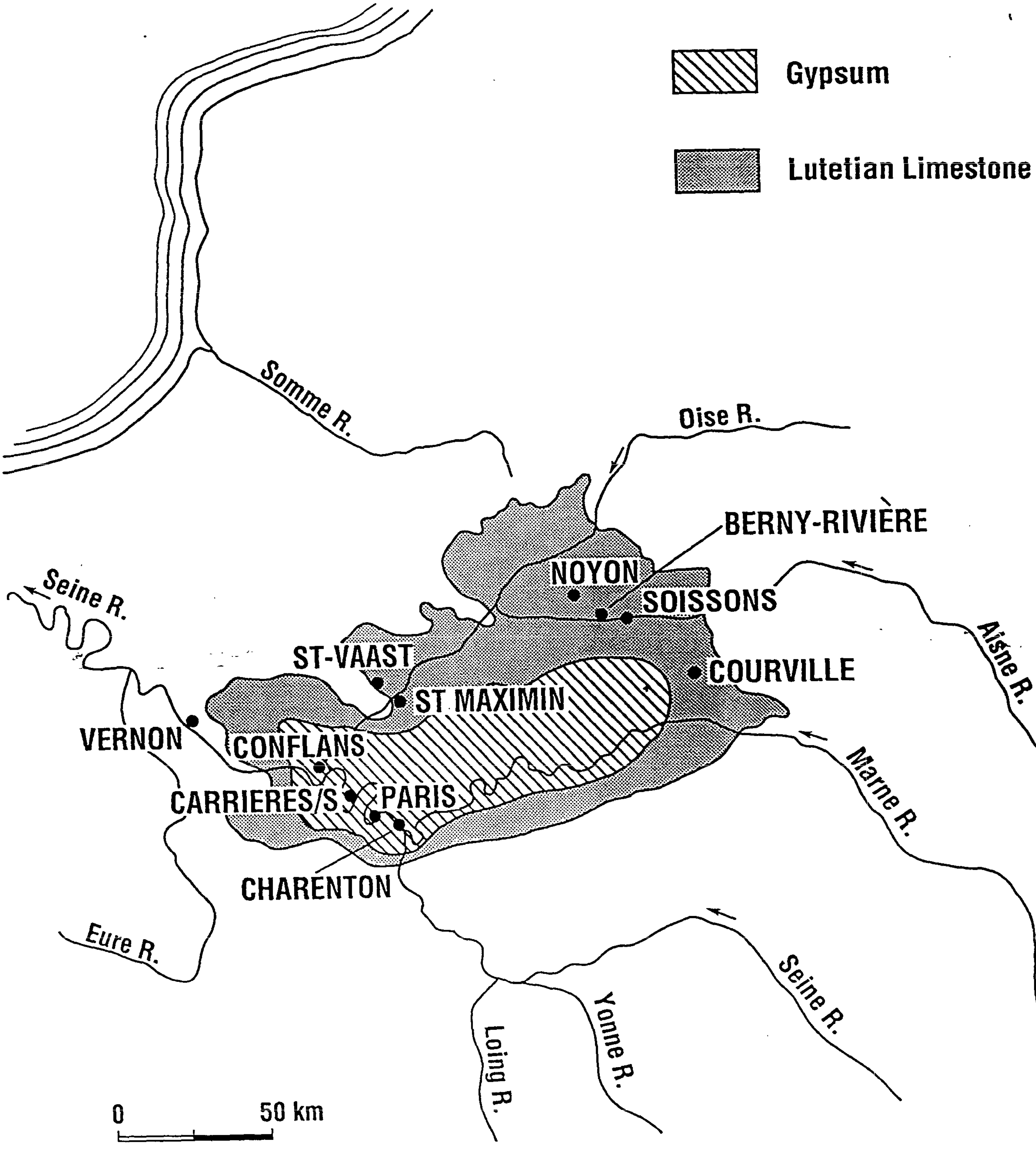

Gypsum
Lutetian Limestone
Somme R.
Oise R.
BERNY-RIVIÈRE
NOYON
SOISSONS
Seine R.
ST-VAAST
COURVILLE
ST MAXIMIN
Aisne R.
VERNON
CONFLANS
CARRIERES/S
PARIS
Marne R.
CHARENTON
Eure R.
Seine R.
Yonne R.
Loing R.
0
50 km

Fig. 5

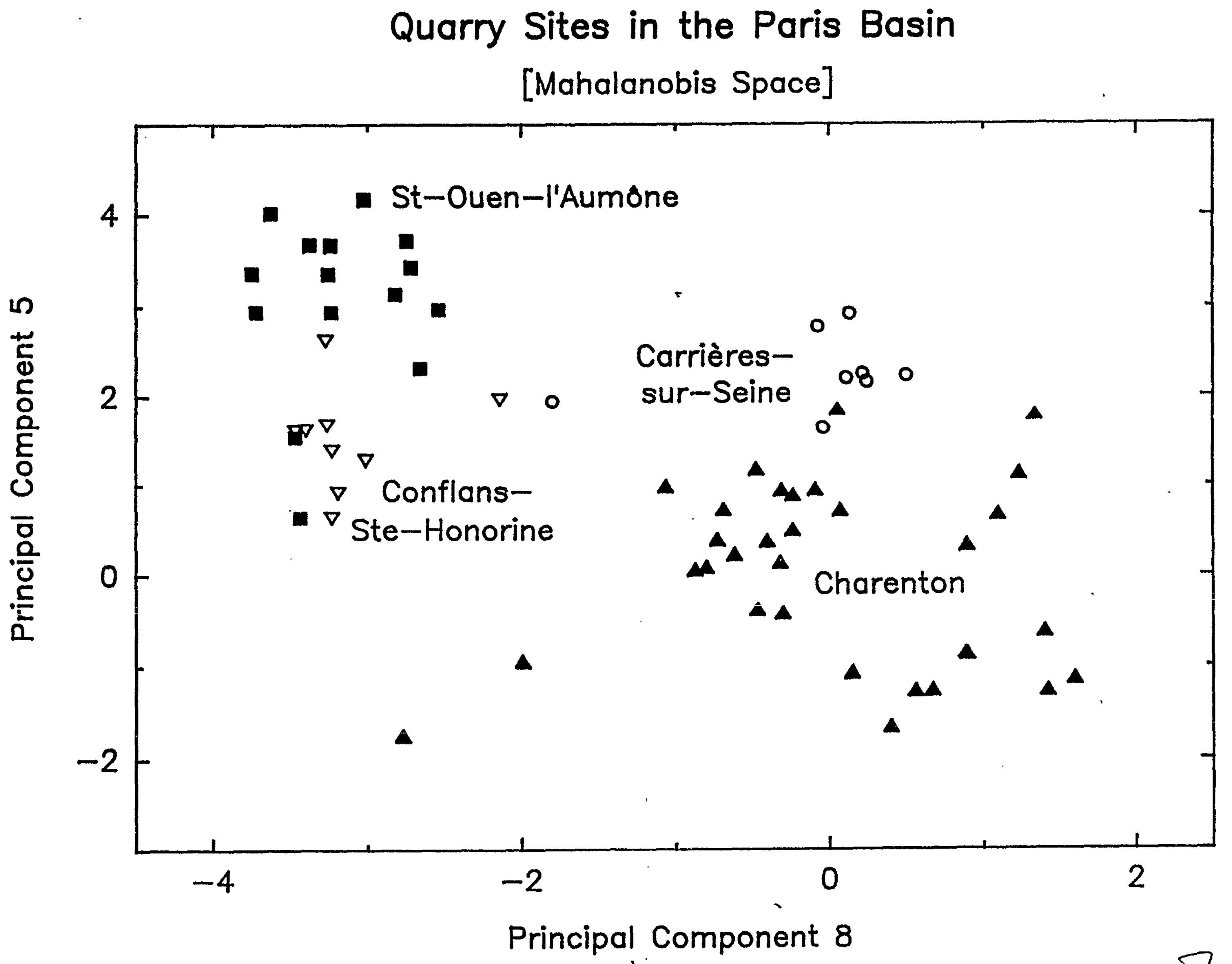
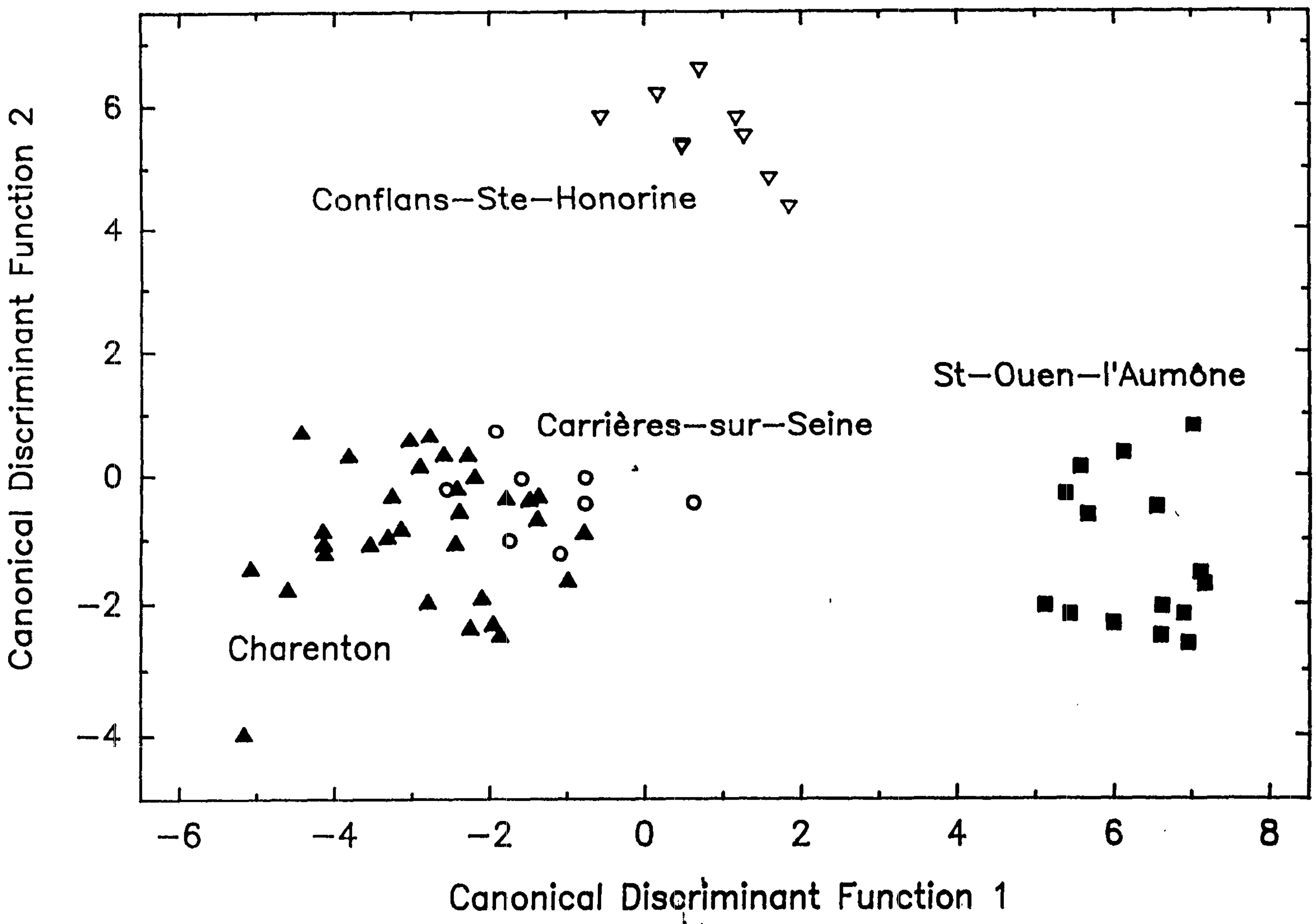

Quarry Sites in the Paris Basin
[Mahalanobis Space]
St–Ouen–l'Aumône
Carrières–
sur–Seine
Conflans–
Ste–Honorine
Charenton
Principal Component 5
Principal Component 8
4
2
0
–2
–4
–2
0
2

Fig 6

Quarry Sites in the Paris Basin

[Discriminant Space]



I. 2

PARIS 23
2/24/93

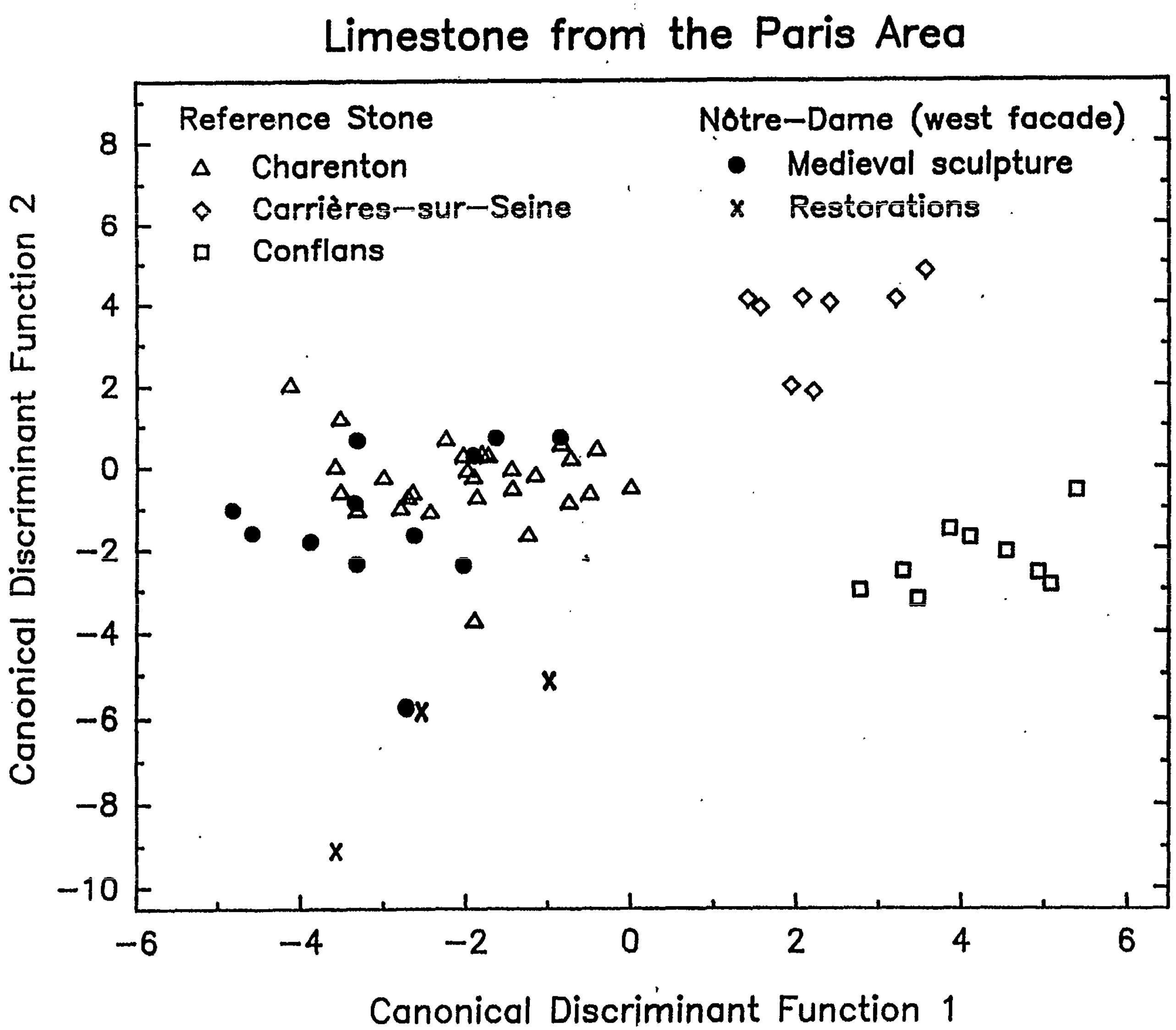
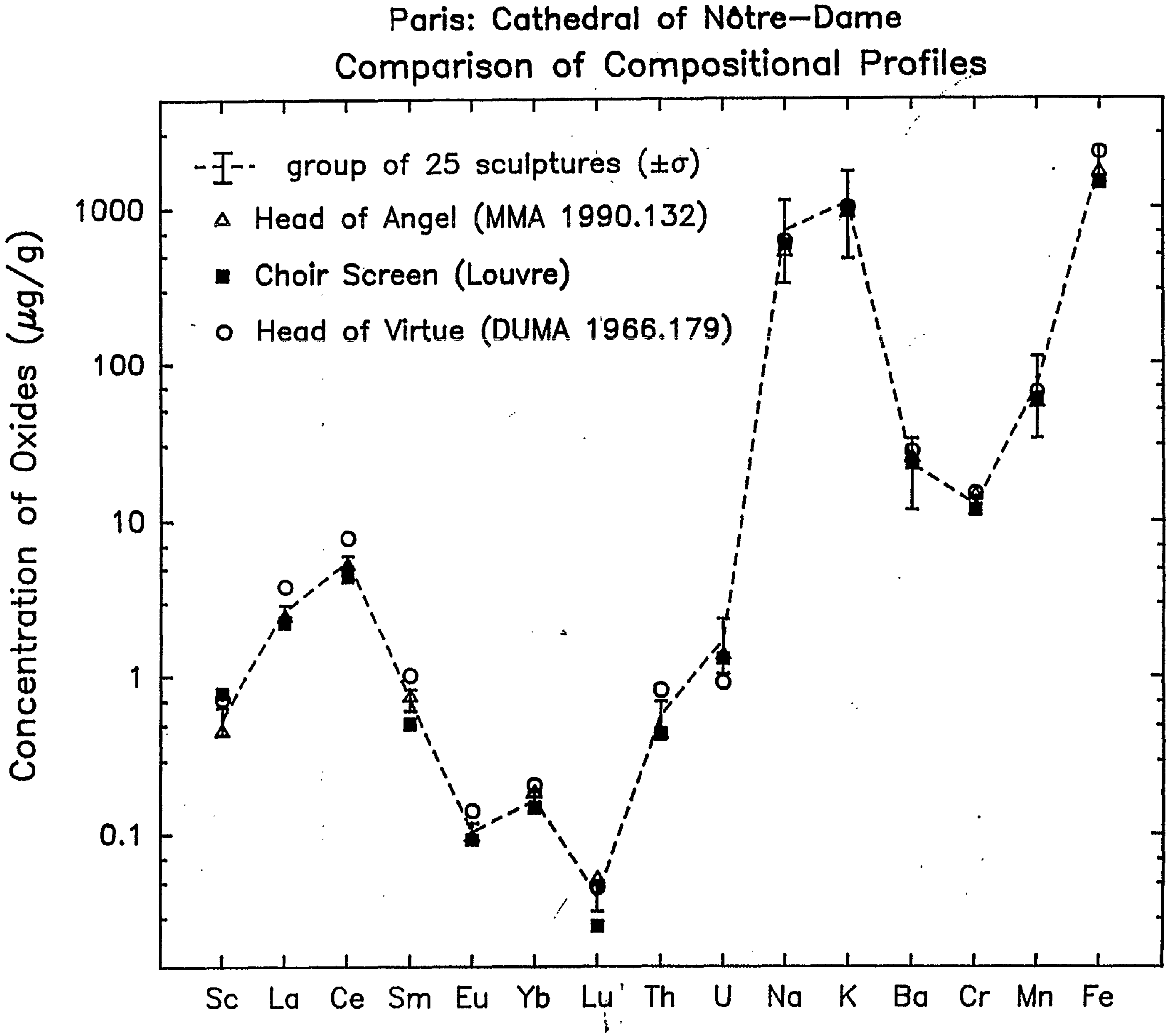


Fig. 8

Fig. 9



Paris: Cathedral of Nôtre–Dame
Comparison of Compositional Profiles
group of 25 sculptures (±σ)
Head of Angel (MMA 1990.132)
Choir Screen (Louvre)
Head of Virtue (DUMA 1966.179)
Concentration of Oxides (μg/g)
1000
100
10
1
0.1
Sc
La
Ce
Sm
Eu
Yb
Lu
Th
U
Na
K
Ba
Cr
Mn
Fe

Fig. 10